NASA ULTRA-SENSITIVE MINIATURE ACCELEROMETER

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ABSTRACT

Using micro-machined silicon technology, an ultra-sensitive miniature accelerometer can be constructed which meets the requirements for microgravity experiments in the space environment. Such an accelerometer will have a full scale sensitivity of 10-2 g a resolution of 10^{-8} g, low cross-axis sensitivity, and low temperature sensitivity. Mass of the device is approximately five grams and its footprint is 2 cm x 2 cm. Innovative features of the accelerometer, which are patented, are: electrostatic caging to withstand handling shock up to 150 g, in-situ calibration, in situ performance characterization, and both static and dynamic compensation. The transducer operates on a force balance principle wherein the displacement of the proof mass is monitored by measuring tunneling electron current flow between a conductive tip and a fixed platen. The four major parts of the accelerometer are tip die, incorporating the tunneling tip and four field plates for controlling pitch and roll of the proof mass; two proof mass dies, attached to the surrounding frame by sets of four “crab-leg” springs; and a force plate die. The four parts are fuse-bonded into a complete assembly. External electrical connections arc made at bond pads on the front surface of the force plate die. Materials and processes used in the construction of the transducer are compatible with volume production.

INTRODUCTION

Microgravity accelerometers used in the harsh environment of space must measure extremely small static and near-static events. Typical applications are experiments on the space shuttle, free flyers, space station, sounding rockets, etc.

The Micro Gravity Acceleration (MGA) sensor is a spring/mass type using a unique "crab-leg" spring support configuration and electrostatic platen force for control of mass movement. Design features of the MGA sensor include electron tunneling tip position detection, electrostatic force feedback, pitch and roll control, electrostatic compensation, and low off-axis sensitivity. A tunneling electron tip provides precision proof mass positioning and measurement for closed-loop control of the sensor. The resulting accelerometer will have a small, 2 cm x 2 cm x 0.6 cm package envelope, a proof mass of 0.2 gin., and a light, 5 gm. (2 OZ) total weight. The targeted operating amplitude range is 10^{-8} to 10^{-2} g with 10^{-9} g resolution and a natural resonance of 12.5 Hertz. The sensitivity, small size and light weight package characteristics are desirable attributes to monitor and control microgravity experiments. The electrostatic force platen design can provide an offset for a constant acceleration field (i.e. earth gravity). Microgravity acceleration changes can be sensed and measured in the presence of a constant field up to 1 g. The electrostatic parking design provides non-operational high acceleration (150 g) load tolerance.

The new simplified lightweight microgravity accelerometer uses micro-machined silicon technology. The spring-supported transducer employs a force balance principle based on electrostaticaly attracted platens. This technique is expected to provide an ultra high sensitivity when the tunneling tip measurement of proximity error is used to hold the mass motionless via a current feedback process. The variation in voltage necessary to maintain mass positioning as a result of this feedback loop will be related to the square root of variation in magnitude of the applied acceleration.

The unique mass-support mechanism uses a dual, four-point crab leg suspension arrangement. This support method minimizes the undesirable cross-axis sensitivity typically present with small transducers. The supported mass is brought into close proximity to the tunneling tip and held stationary using a feedback technique. An added benefit of this technique is that in situ calibration is possible. A known dynamic electrostatic excitation may be applied to the force plate which simulates the result of, and is indistinguishable from, an actual acceleration. Verification of transducer performance and sensitivity values can be undertaken in this manner.

The characteristics cited for improvement over current microgravity accelerometer technology include: a decreased size and mass, higher sensitivity, simplified calibration procedures, health monitoring, and a decreased cost per unit, A novel feature of the desired transducer is that it can be dynamically calibrated in place, In-place calibrations are expected to be highly important when sensitivity changes of the unit might take place over long periods of time, such as during operation on space station or long duration planetary missions.

SI’EDIFICATIONS

The specific technical objectives for the microgravity accelerometer development are:

1. Dimensions: < 2 x 2 x 0.6 cm
2. Total mass: < 5 grams
3. Proof mass: 0.2 grams
4. Amplitude precision range: 10^{-8} to 10^{-2} g
5. Resolution: 10^{-9} g
6. Bandwidth: Static to 10 Hz
7. Cross Axis Sensitivity: < 0.1% of reading
8. Temperature sensitivity: < 0.01 %/°C
9. Operating temperature limits: -20 to +80°C
10. Non-operating temperature limits: -40 to +90°C
11. Non-operating shock limit without affecting calibration: >150 g
12. In-situ static and dynamic calibration during operation
13. In-situ health monitoring and characterization
14. Self test/calibration: internal electrostatic force
15. System interface: Micro computer regulated precision ADC and DAC units

INNOVATIONS

The MGA sensor is an autonomous transducer which provides functional verification as well as perpetual calibration, offset and coefficient compensation. Several innovative features are unique and are patented.

Calibration

The electrostatic attractive force exerted by an electric field between the force plate and the proof mass cannot be differentiated from either the seismic acceleration or mechanical restoration forces. The desired force arises from an applied voltage on the force plate which is previously correlated to a predetermined force on the movable member. By observing the response of the feedback controller to the applied voltage on the force plate, the entire device may be calibrated. In fact, a large range of applied voltages corresponding to a range of applied forces may be used in succession to internally calibrate the micromachined transducer. The advantage is that the device is readily calibrated or re-calibrated remotely and with great precision without any external calibration equipment of the type typically required.

Characterization

In order to characterize various parameters (such as frequency response) of a micro-machined transducer, the desired force applied by the control apparatus is a test stimulus signal. This range of parameters may include, for example, frequency response, phase response, linearity, hysteresis and the like.

Static and Dynamic Compensation

It may be desired to compensate for a large ambient force so that only small differentials are measured by the micro-machined transducer. The desired force is one which is equal and opposite to the force exerted on the movable member by the ambient force. This type of compensation requires the desired force to be fairly constant over time, and is therefore a type of static compensation.

Three micro-machined accelerometers may be integrated in an inertial sensor, each accelerometer being aligned, to within a manufacturing error, along a respective one of three orthogonal axes. The resulting cross-coupling between measurements otherwise deemed to be orthogonal is measured precisely after assembly of the inertial measurement device. During calibration and operation, the vector forces are measured using two known orthogonal forces to determine the proper correction for the third individual sensor. The same process is repeated to determine the correction for each of the sensors in a triaxial configuration. These correction factors are then applied to the appropriate accelerometer's force plate and the *cross* axis error in the measured data is compensated for.

A fixed bias maybe deployed in determining the static characterization of a transducer, such as providing "free" levitation of a sensor element in a fixed gravitational field.

A small single cell battery of about a volt, can create a large attractive force between two micro-structured platens. With a good insulator, the leakage current is negligible, permitting maintenance of a retention force for the cell life of about a decade. In micro-structured accelerometer, application of this electrostatic retention facilitates a simple mechanism for caging the proof mass that will withstand accelerations in excess of 150 g for launch, etc.

MECHANICAL DESCRIPTION

The transducer design is based on a four dic configuration as shown in Figure 1. The top die in the figure is referred to as the tip die which is shown in more detail in Figure 2. The tip die has at its center an electron tunneling tip. The tip will be approximately 3.75 μm high. Two identical dies are bonded together to form the proof mass. These dies arc comprised of a border region and the proof mass as shown in the center of Figure 3. The proof mass is 1 cm (10,000 pm) across. 'lie lowest dic is referred to as the force plate. Figure 4 presents the top and bottom views of this die.

CONSTRUCTION

Tip Die

The tip die, the most complicated structure in the assembly, has its basic fabrication process illustrated in Figure 5. Key specifications of the tip die are listed in Table 1. It not only incorporates the tunneling tip, but contains 4 field plates to control the pitch and roll of the proof mass as well as its position. The tip die must also accommodate the bonding method use to assemble the four separate dies that comprise the accelerometer. Two separate metal layers are required. The first layer is isolated from the second by a **0.5 μm** oxide layer. The first metal layer is used as the tip metal. A three metal composite is used consisting of chrome/gold/chrome. Chrome layers are used to enhance adhesion to the substrate (nitride coated silicon) and to the isolation oxide layer. The top chrome layer of this composite metal layer is removed to expose the gold layer as the tip metal.

The second metal layer, the same metal used as the bonding layer, is aluminum/germanium, the preferred choice because it is easily deposited, inexpensive and has a low bonding temperat ure.

The center region of the die is recessed with respect to the bond perimeter and bond pads. This is required to obtain a spacing between the field plates and the proof mass. When this die is bonded to the proof mass, the perimeter will form a hermetic seal with the bond pads, mechanically bonded and electrically connected to their counterparts on the proof-mass die. This electrical connection scheme is a key feature of the design. By interconnecting the die in the bonding processes, all electrical connections to the completed accelerometer can be made from its front surface.

The electrically insulating oxide layer is removed from the tip and its surrounding area, exposing the tip metal. The electrical contact to the tip is accomplished with the first metal layer which is connected by a single thin lead to the bond pad. The second metal layer which forms the field plates, bond perimeter and bond pads is deposited above the first metal layer. The cross in the center of the bond perimeter, which is electrically grounded, is used to shield the tip metal lead form the influence of the. electric fields that will exist in the vicinity of the field plates. Because of the recessed nature of the center of the die, the center cross of the bond perimeter will not take part in the bonding process. The cross is open at the very center to expose the tip below.

To connect the force plates electrically to the bond pads, holes are cut in the oxide layer above the first metal in the vicinity of the force plates. This allows the force plates to contact the first metal layer. The first metal layer is patterned in such a way as to connect each force plate electrically to its associated bond pad. The bond pads also contain a connection between first and second metal.

Proof Mass Die

Key specifications of the proof mass die are given in Table 2 and the basic steps in the fabrication process are shown in Figure 6. The proof mass is assembled from two identical die. The top dimension is 1 cm or 10,000 pm. The proof mass is held to the surrounding frame by a set of springs affectionately referred to as ‘crab legs.’ The target thickness of the crab legs is 25 μm. Each individual crab leg is divided into three spring sections, two short ones and one long one. The length of the short must also accommodate the bonding method use to assemble the four separate dies that comprise the accelerometer. Two separate metal layers are required. The first layer is isolated from the second by a 0.5 μm oxide layer. The first metal layer is used as the tip metal. A three metal composite is used consisting of chrome/gold/chrome. Chrome layers are used to enhance adhesion to the substrate (nitride coated silicon) and to the isolation oxide layer. The top chrome layer of this composite metal layer is removed to expose the gold layer as the tip metal.

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The proof mass die is maintained at essentially ground potential and the surface of the proof mass is completely covered by metal. At the perimeter of the die, electrical contact between bond pads is routed to facilitate the scheme of front surface contact only, as described above.

The eutectic bonding metal is applied before the anisotropic etch procedure to prevent metal deposition on the backs of the springs.

Force Plate Die

Key specifications of the force plate die appear in Table 3 and the basic steps in the fabrication process are shown in Figure 7.

The force plate die, similar to the tip die, uses a two metal process to provide a bond perimeter which is not electrically connected to the force plate. A contact pad to this perimeter metal is provided in order to set the potential. The force plate is fabricated in first metal, which may simply be a single chrome layer similar to that used on the tip wafer. The force plate must be covered with a thin 1000A oxide layer . The purpose of this oxide layer is to prevent an electrical contact between the proof mass and the force plate when the proof mass is being clamped electrostatically. Choices for the bond perimeter and contact layer (second metal) are identical to those described for the tip wafer.

The 'top view' section of Figure 4 shows the locations of the bond pads and specifies their various functions

CONCLUSIONS

Silicon micromachining is rapidly becoming the dominant method for producing state-of-the-art sensors in the world today. Even laboratory tunneling tip accelerometers have been developed but, until now no one has resolved how the delicate mechanisms of sensitive accelerometers can be protected and a robust sensor engineered.

The recursive design process that resolved the mechanisms and machining processes to realize them has been arduous but rewarding. The MGA sensor described in this paper will provide experimenters with the capability for highly sensitive acceleration measurements using a device of extremely small size and mass. This sensor has patented innovative features which include in situ calibration, in-situ characterization and self test, state and dynamic compensation, and caging. The sensor also has low cross-axis sensitivity and negligible temperature sensitivity ($10^{-5}\mu g/^{o}C$). Materials and processes used in the construction of the transducer are compatible with volume production.

ACKNOWLEDGMENTS

This paper represents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology and at the Microsensor Laboratory, Northeastern University under contract with the National Aeronautics and Space Administration.

Table 1
Key Specifications of the Tip Die

Design Characteristic	Specification	Tolerance
Tip to Ground Capacitance	100 pf	+/-20 pf
Control Plate to Substrate Capacitance	100 pf	+/-20 pf
Control Plate to Proof Mass Capacitance	100 pf	+/- 1 µf
Control Plate to Tip Ground Capacitance	0.2 pf	max.
Voltage to overcome 1 g	5	+/-1
Tip to Proof Mass Proximity	o	+/-0.2 µm
Tip Height	3.5 µm	+/-0.5 µm
Bond Metal Thickness	1 µm	+/-0.1 µm
Insulating Layer Thickness	0.5 µm	+/-0.05 µm

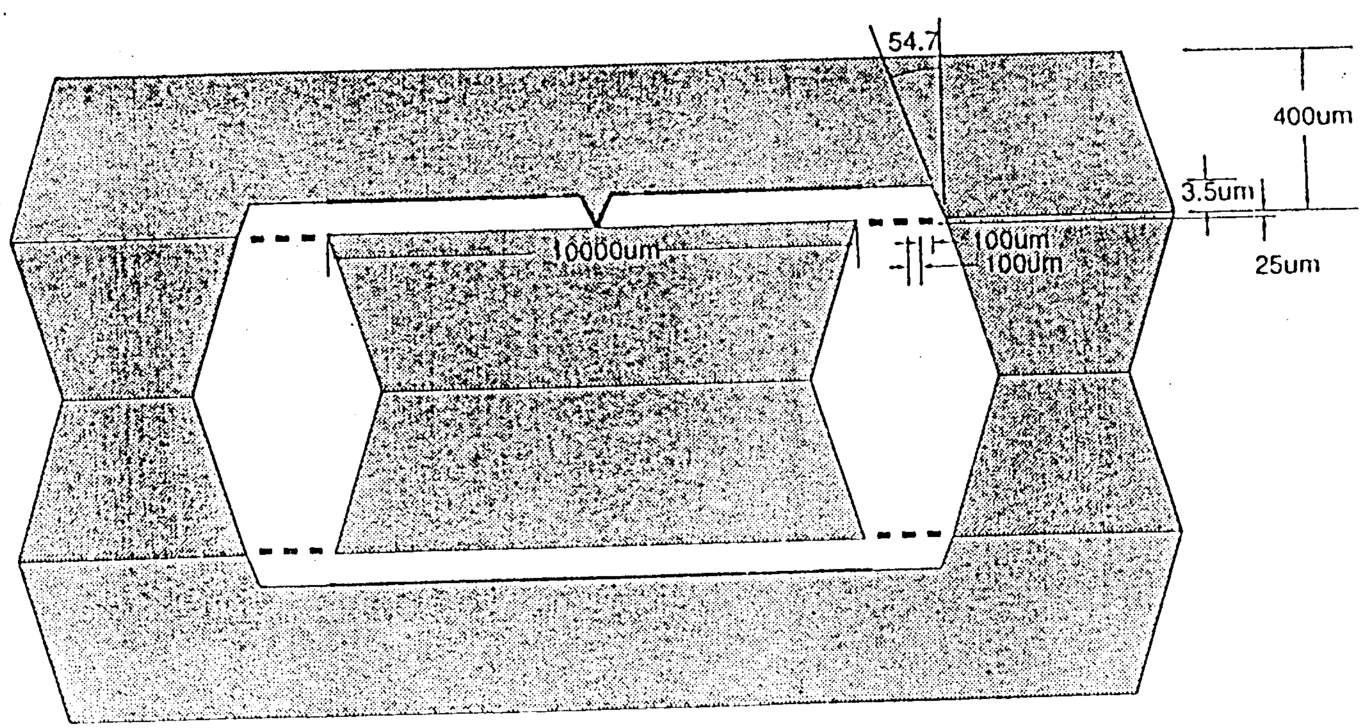


Figure 1. ACCELEROMETER ASSEMBLY

Table 2

Key Specifications of the Proof Mass Die

Design Characteristic	Specification	Tolerance
Mass	0.18 gm	+/-0.005 gm
Volume of Proof Mass	7.55 x 10-2 cm^3	
Spring Thickness	25 µm	+/-5 µm
Spring Width	100 µm	+/-5 µm
Spring Length	5000/9800 µm	+/-5 µm

Table 3

Key Specifications of the Force Plate Die

Design Characteristic	Specification	Tolerance
Force Plate to Substrate Capacitance	5 x 10^{-2} µf	+/-2 x 10-2 µf
Voltage to overcome 1 g	10	+/-2
Bond Metal Thickness	1 µm	+/-0. 1 µm
Insulating Layer Thickness	1000 A	+/-250 A
Depth of Depression	5 µm	+/-0.05 µm
Max. Holding Voltage	10	
Holding Force @ 1.4v	96 g to 265 g	

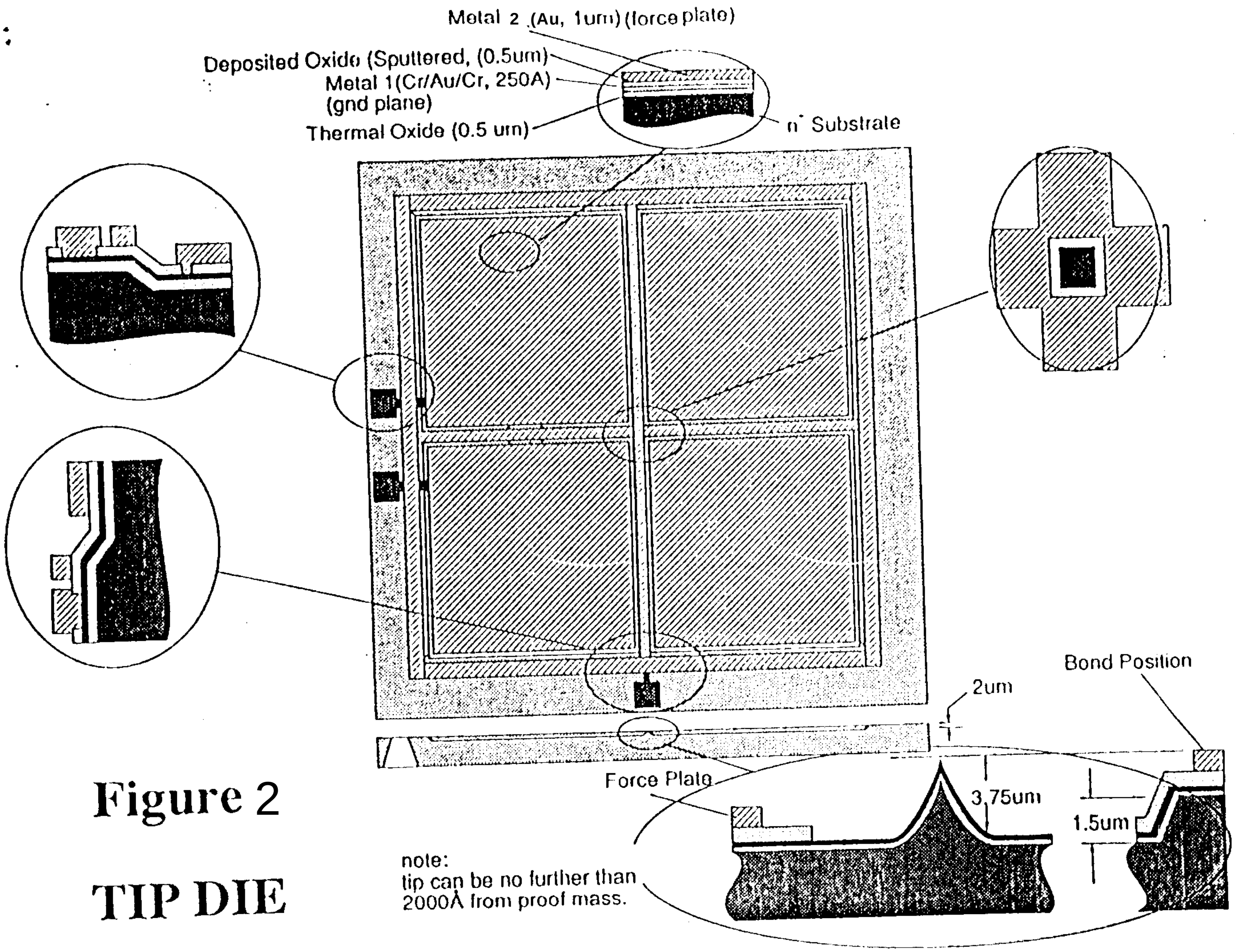
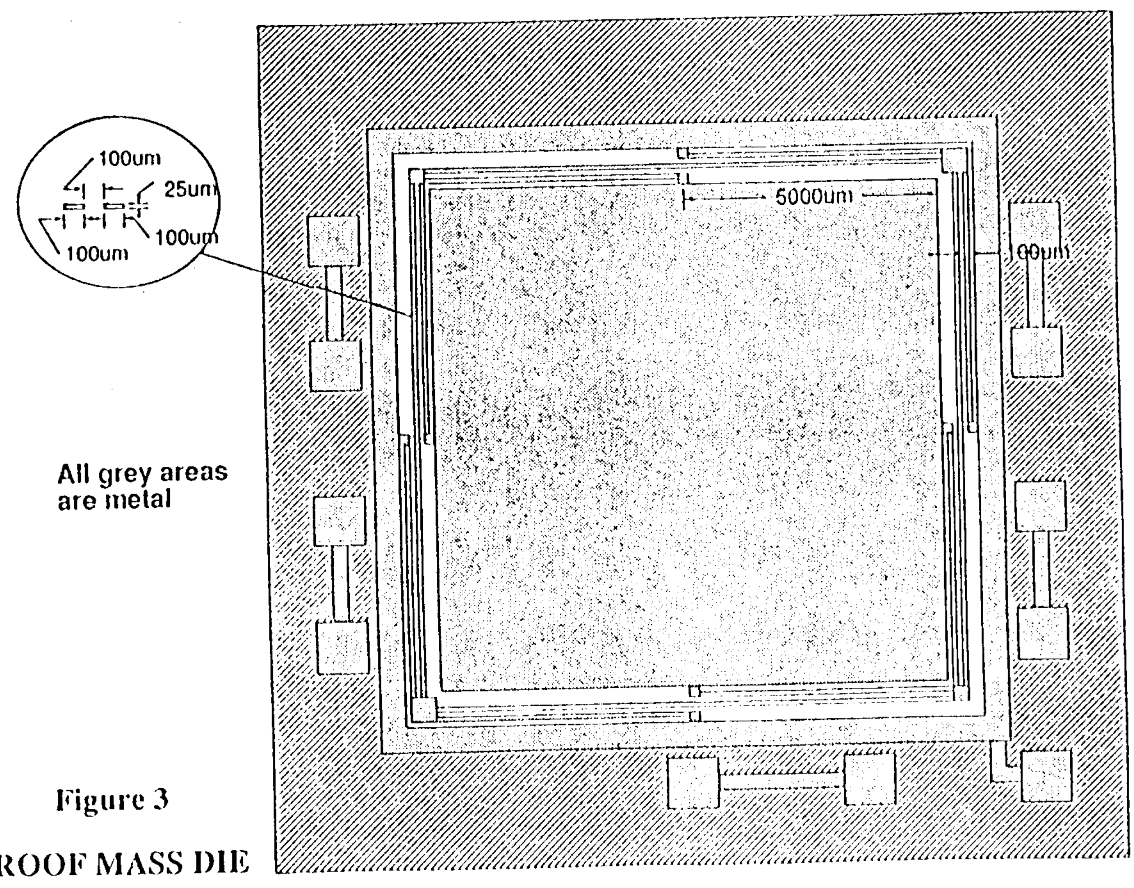


Figure 2

TIP DIE

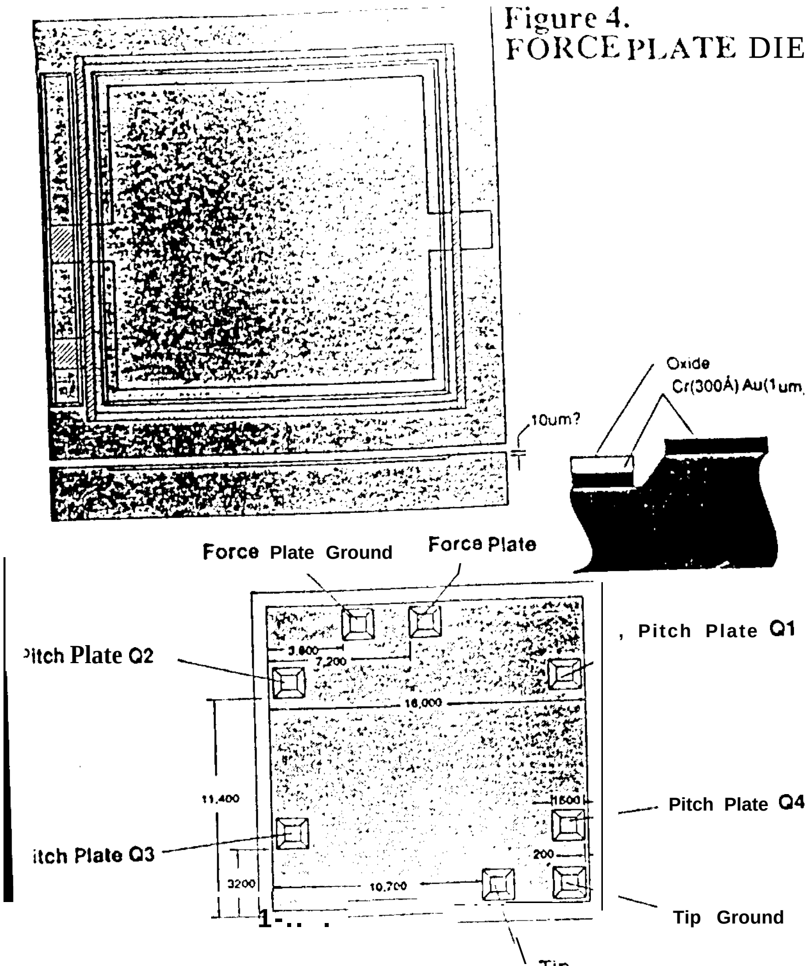


All grey areas are metal

Figure 3

PROOF MASS DIE

Figure 4.
FORCE PLATE DIE



top view showing wire bond positions}

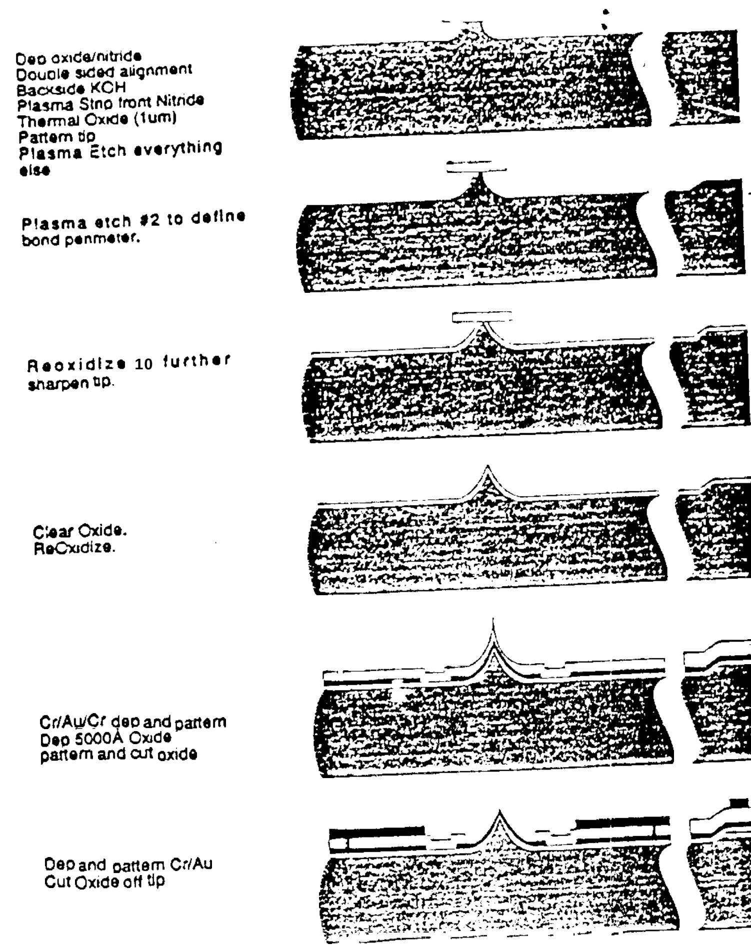


Figure 5. TIP DIE FABRICATION PROCESS

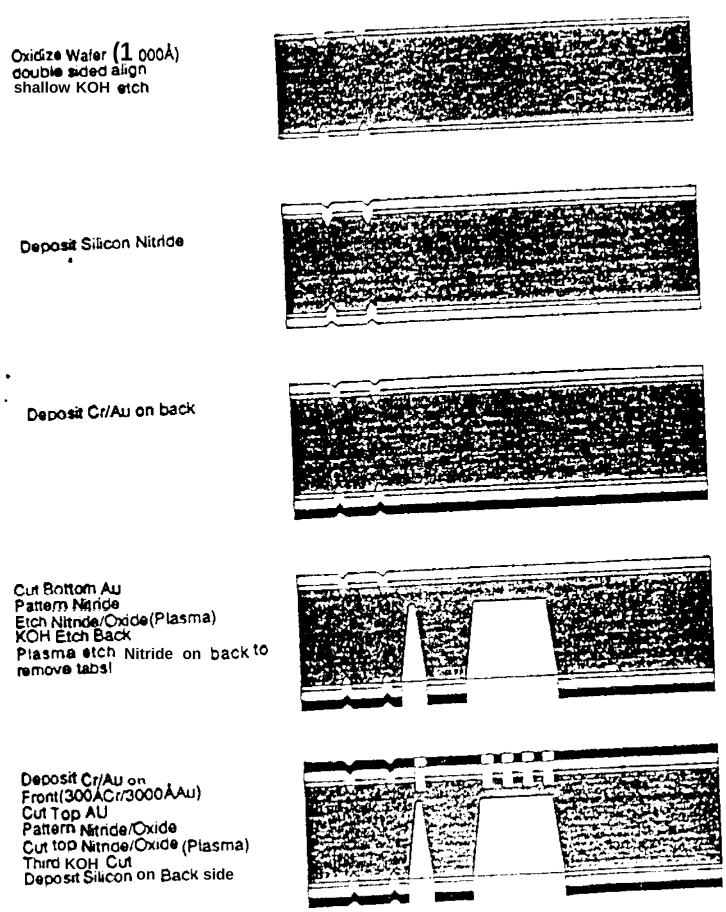


Figure 6. PROOF MASS DIE FABRICATION PROCESS

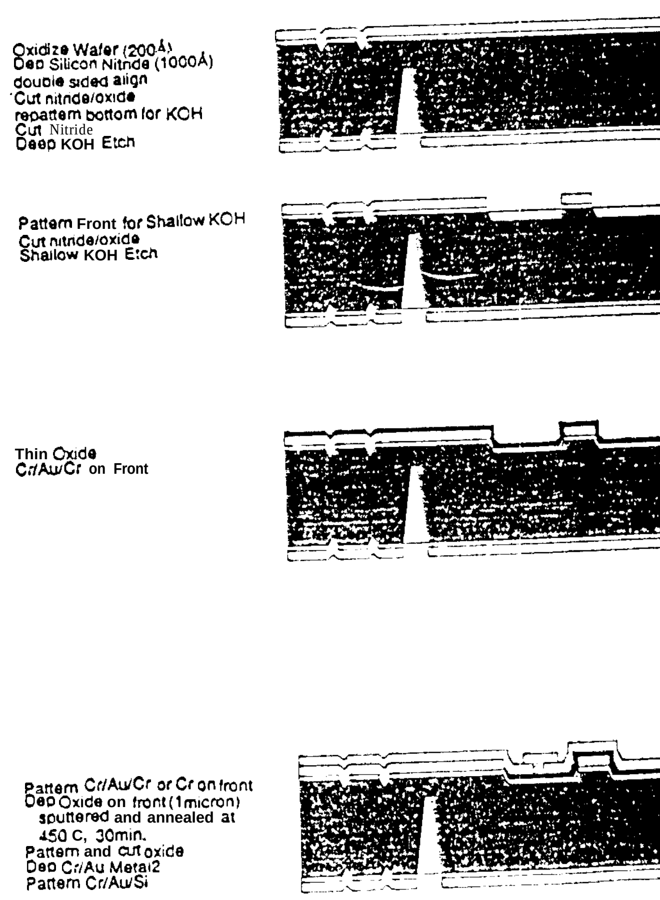


Figure 7. FORCE PLATE DIE FABRICATION PRO

‘ MICROGRAVITY MEASUREMENT GROUP CONFERENCE

Huntsville Alabama
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AGENDA

- Technical overview
- Innovations
- silicon fabrication
- Testing

DESIGN FEATURES

- Electrostatic force balance
- In-situ calibration
- Electrostatic caging of proof mass
- Reduced off-axis acceleration due to proof mass centering
- Tunneling tip position detection
- Buik micromachined using four wafers

SAMS ENVELOPE

TECHNICAL OVERVIEW

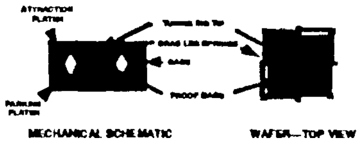
❑ Accelerometer Specifications

● RANGE	10^{-4} to 10^{-2} g
● Resolution	10^{-8} g
● BANDWIDTH	Static 1010 Hz
● SHOCK LIMIT	● 150g
● DIMENSIONS	● 2x2xo.6cm

■ Features

- . Silicon micromachining (Northeastern University)
- ● Proof mass motion detected by electron tunneling effect
- ● Electrostatic parking (caging) used to survive handling, launch, etc., and letdown

DESIGN SKETCH



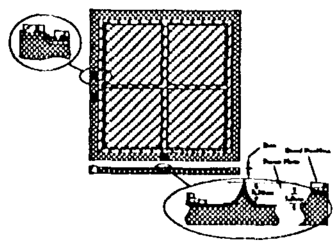
TRANSDUCER SENSITIVITY COMPARISON

Transducer Type	Capacitive	Tunneling
Active Area	10 μm X 10 μm	10 Å x 10 Å
Electrode Separation	1 μm	5 Å
Bias Voltage	1 Volt	100 mv
Measurement Frequency	200 kHz	DC - 10 mHz
1% Transducer Signal	90 Å	0.004 Å

ADVANTAGES of the ELECTRON TUNNELING POSITION SENSOR

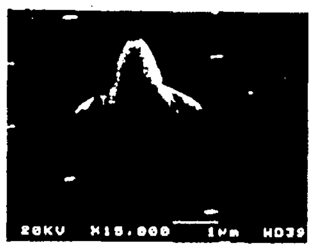
- Improved sensitivity
  - Approximately 20,000 times mom sensitive than conventional (capacitive) transducers. Allows use of less sophisticated electronics. Sensitivity can be traded off to improve other characteristics such as bandwidth, resonance linearity . . . .
- Microscopic active area
  - ton sensitive to contamination. Allows construction of micro-scale sensors
- Low power consumption
- Simple electronic control system
- Compatible with silicon micromachining technology

TIP

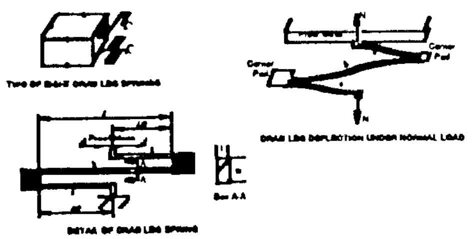


TIP WAFER

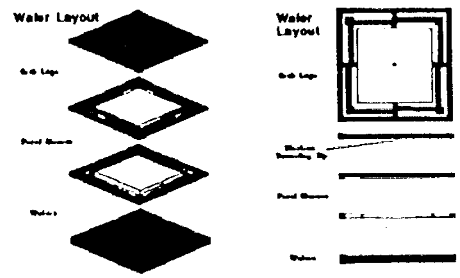
TUNNELING TIP



SPRING DESIGN

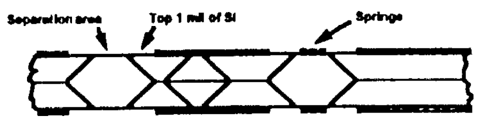


EXPLODED WAFERS



ASSEMBLY

■ 1 Proof mess wafers are bonded

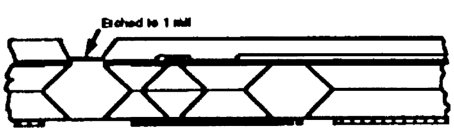


ASSEMBLY

● 2 — Silicon etched on one side to separate die and make springs

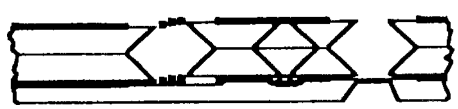
ASSEMBLY

■ 3 — Au/Si bond holding plate wafer to top wafer



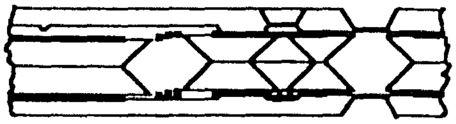
ASSEMBLY

❑ 4 — Flip wafers and etch Si on top wafer



ASSEMBLY

- 5 — Bond tip wafer



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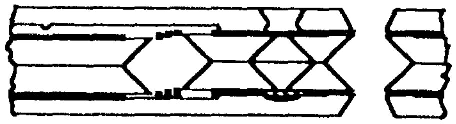
ASSEMBLY

- 6 — Etch silicon on both wafers to separate die



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ACCOMPLISHMENTS

- Hardware
  - Wafers bonded together
  - Tunneling current observed — unsprung & STM
  - Revision of tunneling tips
  - "Crab" leg springs deep etched
- Electronics
  - Tunneling current amplifier complete
  - Data acquisition system configured
  - Capacitive sensing circuit tested
  - SAMS interface designed
- Test & calibration — site evaluations
  - JPL Gyro Lab
  - Inertial Guidance Facility, Holloman AFB

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SILICON FABRICATION

- Bonding of silicon layers — germanium aluminum tasted
- Clean deep plasma etching process for springs
- Unsprung unit characterization of tunneling current
- Scanning Tunneling Microscope (STM) surface profiling and tunneling current characterization
- Tunneling tip fabrication options evaluated

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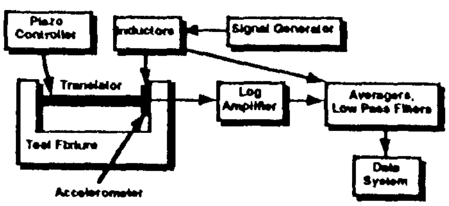
DATA ACQUISITION SYSTEM



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MOUNTED TEST CHIP

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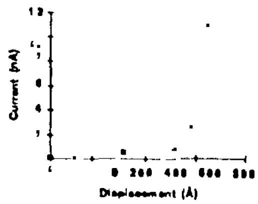
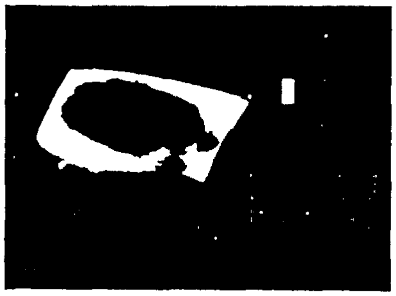
TESTING "UNSPRUNG" ACCELEROMETER

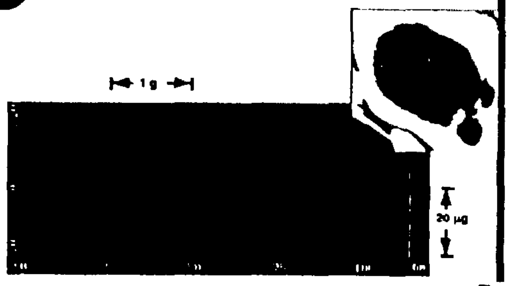
- Rugged
- Used to study tunneling current
- Piezoelectric translator pushes on proof mass



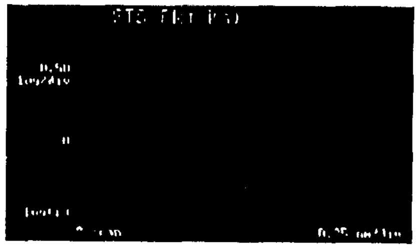
STM 3D SURFACE PROFILE



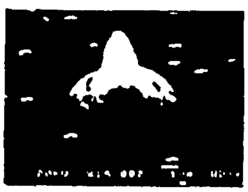
STM 2D SURFACE SHAPE



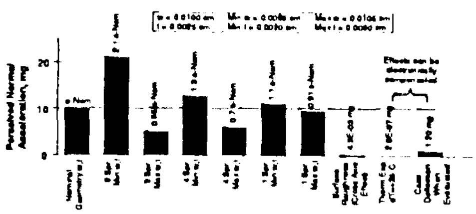
DISTANCE — CURRENT PROFILE



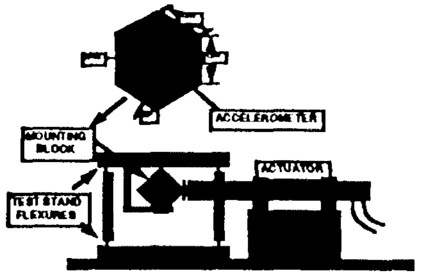
SHARP — BLUNT TIP PHOTOS



PERCEIVED NORMAL ACCELERATION DUE to PARAMETER Variations



ACCELERATION STIMULUS TESTBED



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SITE EVALUATION

- Goal — Find convenient sits for ground-based testing
- Strategy
  - Characterize candidate sites
  - Model ● culammctar ideal response (0)
  - Compute predicated on-site response
- Results
  - JPL Gyro Lab suitable for system checkout
  - Inertial Guidance Facility, Holloman AFB has half the noise of JPL, ● daqumte for limited characterization

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RESPONSE PLOTS

- Response of accelerometer, Q = 500

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RESPONSE PLOTS

- Seismic noise plot on quiet JPL pier

JPL

m

HOLLOMAN NOISE PLOT

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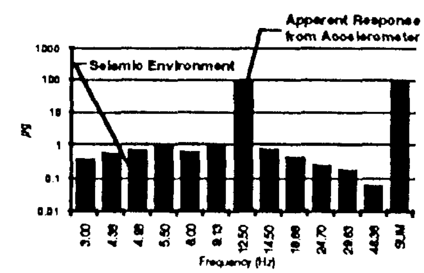
NET RESPONSE — JPL PIER



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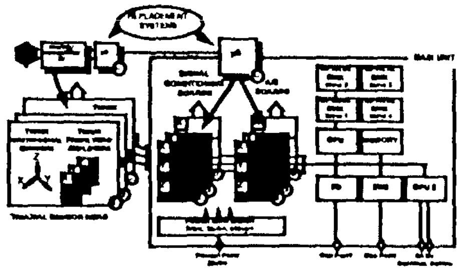
SHUTTLE FLIGHT MEASUREMENT SYSTEM



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SUMMARY

- Silicon machined accelerometer has oniy a couple of outstanding fabrication details to be resolved
- Caltech has patented the unique "caging" and in-situ calibration/ characterization features of device
- Zavracky and Hartley Intend to patent the letdown technique

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SUMMARY ((X)NT'D)

- An abridged version of mechanical model is ready for publication in IEEE/ ASME Journal of Micromechanical Systems
- A silicon machining technical publication is In preparation
- Bench electronic circuits have been developed end tested

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SUMMARY (CONT'D)

- Ground test environments and stimulus have been identified and developed
- Flight stimuli and SAMS interface systems have been designed
- We have passed the tunneling current milestone
- We have not run into any show stoppers

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